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MODEL FOR ESTIMATING NAVAL FORCE LEVELS

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INSTITUTE FOR DEFENSE ANALYSES
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PREFACE

This study was initiated in support of a task performed by the System Evaluation Division of IDA for the Office of the Secretary of Defense (Program Analysis and Evaluation, Naval Forces Division).[1] The principal results of that task are reported in Reference 1, which was a review of a submarine force-level study performed by the Joint Staff (References 2 and 3). The present study was completed with support from IDA's Central Research Program. The author is grateful to Mr. Thomas L. Gibson, Director of the Naval Forces Division within OSD (PA&E), and to Dr. David L. Randall, Director of the System Evaluation Division at IDA, for their guidance and support. The author would also like to thank Dr. Alfred I. Kaufman and Dr. Kevin J. Saeger for reviewing the manuscript, Mr. John F. Donahue for editorial assistance, and Mrs. Cynthia S. Maloney for typing and preparing the document.

1 *Impact of Non-Submarine Systems on Attack Submarine Force Levels*, Contract No. MDA903-89-C-0003, Task Order T-Q1-1191, 23 July 1993.

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CONTENTS

FIGURES

TABLES

EXECUTIVE SUMMARY

This paper describes a simple spreadsheet model for estimating the number of naval units (ships or submarines) required given:

- the number of deployment stations and their characteristics (distance, transit speed, deployment time);
- the number of operating days per year that each unit must dedicate to self-training;
- the annual number of unit-days of training and services that the force must provide to other elements of the Fleet;
- the fraction of the force that is in overhaul or long-term maintenance at any given time;
- the in-port maintenance requirements due to deployments and non-deployed operations; and
- constraints on personnel operating tempo expressed in terms of the minimum time between deployments and/or the maximum fraction of time spent away from home port.

The model's input can be adjusted to address both Peacetime Presence and Conflict scenarios. When combined with a simple cost model, the force-level model can be used to explore cost tradeoffs and sensitivities. As an example, the cost of an attack submarine force that meets specific deployment requirements is determined as a function of the number of crews per submarine.

We stress that the purpose of this paper is to describe a <u>tool</u> that can be used to address force-level issues: no specific force-level findings or recommendations are presented. We also stress that the model does not address the warfighting effectiveness of a given number of units. A separate effectiveness analysis would have to be coupled with the force-level model to explore cost-effectiveness issues.

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I. INTRODUCTION

During the Cold War, military force levels tended to evolve. For example, the number of attack submarines planned for the US fleet would be incremented or decremented from year to year on the basis of intelligence estimates of the number of units in the Soviet fleet, the perceived capabilities of US vs. enemy forces, domestic economic conditions, and the general attitude toward defense needs. The fall of the Soviet Union and the resultant fall of US defense budgets, however, have brought an end to this evolutionary process.

As evidenced, for example, by the "Bottom-Up Review" (Reference 4), force levels must now be justified from "first principles". For naval forces this is a two-step process. First the operational requirements are stated (e.g., the number of stations to be manned). These are, of course, judgmental, but the rationale for them generally involves: a (somewhat agreed upon) planning scenario(s), the missions assigned, and requirements to support other types of forces.

The second step is to determine the size of the force required to meet the stated requirements. This step may be less judgmental than the first, but is still somewhat complicated. This paper describes a methodology for addressing this second step: given operational requirements in terms of stations to be manned, services to be provided, maintenance requirements and constraints on personnel operating tempo, how large must the force be? The methodology allows for the rapid estimation of changes in force levels as force requirements are varied, and enables the impact on force levels due to operating tempo, service requirements, maintenance cycles, etc. to be rapidly assessed. Although the examples will address submarine force levels, the model is applicable to all types of naval units. In addition, a cost model is described that enables force costs to be estimated.

We stress, however, that this paper is methodological, that is, it provides tools for exploring the above issues. To draw explicit force level conclusions would require much more careful determination of fleet requirements, operational constraints and costs. However we do describe examples that enable us to determine particular areas that may benefit from closer scrutiny.

In the next chapter we summarize the force-level model and apply it to the Peacetime Presence, Conflict, and Surge scenarios. In each case we illustrate the model using representative examples. We then summarize a cost model and apply it and the force-level model to the example of multiple crewing for attack submarines. Finally, we discuss some other potential applications and issues. In Chapter III we derive the force level model and, in an Appendix, we present a spread-sheet version (Excel).

II. SUMMARY AND EXAMPLES

A. FORCE LEVEL MODEL

This section summarizes the general model. We first list the input and give formulas for the output, and then describe the resultant deployment cycle in terms of its components. See Chapter III for more detailed definitions and derivations.

1. Input/Output

The total force level, N, is given by

$$N = \frac{1}{A}\left(N_{OP}^{D,\,T\&S} + \Delta N(h)\right) + N_R$$

where we have denoted:

- A: Availability (fraction of force not in long-term overhaul)
- N_R: Number of non-deploying units

  $N_{OP}^{D,T\&S}$: Number of operational units required for deployments and training and services

  $\Delta N(h)$: Number of additional operational units required so that crew operating restrictions can be satisfied

and where "•" denotes input.

$N_{OP}^{D,T\&S}$ is given by:

$$N_{OP}^{D,\,T\&S} = Z + \frac{1}{Y - \left(1 + t_N\right) d_{ST}}\left[Y Z t_D + \left(1 + t_N\right)\left(d_{ST} Z + S\right)\right]$$

where we have denoted:

- Y: 365 (days/year)
- d_{ST}: Number of operating days dedicated to self-training per unit per year
- S: Number of unit-days of training and services (T&S) provided per year by the total force

- t_D: A constant. When t_D is multiplied by the deployment time, it yields the in-port maintenance time due to the deployment.
- t_N: A constant. When t_N is multiplied by the non-deployed operations time, it yields the in-port maintenance time due to the non-deployed operations.

$$Z \equiv \sum_{i=1}^{n_S} Z_i \equiv \sum_{i=1}^{n_S} \frac{u_i}{1 - T_i^{TR} / T_i^D}$$

- n_S: Number of stations
- u_i: Number of units required on i^{th} station simultaneously

and where the (two-way) transit time T_i^{TR}, is given by:

$$T_i^{TR} = \frac{2\,D_i}{24\,v_i} \quad \text{(days)}$$

- D_i: Distance to i^{th} station (nmi)
- v_i: Transit speed to i^{th} station (kts)
- T_i^D: Deployment time for i^{th} station including transits (days)

and, again, where the "•" denotes input.

$\Delta N(h)$ is given by:

$$\Delta N(h) = \frac{h\,Y\,Z}{Y - \left(1 + t_N\right) d_{ST}}$$

where h is the multiple of T_i^D spent in port to satisfy T_0^{AR} and P_0 constraints (i.e., in addition to required maintenance periods):

$$h = \max\left\{h\left(T_0^{AR}\right), h\left(P_0\right)\right\}$$

$$h\left(T_0^{AR}\right) = \max\left\{0,\ T_0^{AR} - \frac{d_{ST}}{\left(1 + t_N\right) Y}\left(T_0^{AR} + 1\right) - \frac{S}{YZ}\left(t_N + 1\right) - t_D\right\}$$

where

- T_0^{AR}: Minimum allowed turn-around ratio:

$T_i^{AR} \geq T_0^{AR}$ where $T_i^{AR} \equiv T_i^N / T_i^D$ and T_i^N is the non-deployed period.

$$h(P_0) = \max\left\{ 0, \frac{\left(Y - (1 + t_N)\, d_{ST}\right)\left(\frac{S}{ZY} + 1\right)}{YP_0 - d_{ST}} - 1 - (1 + t_N)\frac{S}{YZ} - t_D \right\}$$

where

- P_0: Maximum allowed PERSTEMPO:

$P_i \leq P_0$ where P_i, the PERSTEMPO, is the fraction of a deployment cycle spent away from home port.

2. Deployment Cycle

In determining the above total force level, we also determine the total cycle time for each deployment. We present that breakdown here. The total cycle time is given by the sum of the deployment time and the ("non-deployed") time between deployments not counting long-term overhaul periods (all times are in days, and, as before, "•" denotes input):

$$T_i^D + T_i^N \quad \text{(Total cycle time for } i^{th} \text{ deployment)}$$

- T_i^D (Deployment time)

$$T_i^N = T_i^{AR} T_i^D \quad \text{(Non-deployed time)}$$

$$T_i^{AR} = \frac{Y}{Y - (1 + t_N)\, d_{ST}} \left(t_D + (1 + t_N)\left(\frac{d_{ST}}{Y} + \frac{S}{YZ}\right) + h \right) \quad \text{(Turn-around ratio)}$$

where the terms on the right-hand side are given above in Section II.A.1. (Note that T_i^{AR} is independent of i. This is due to our assumption that non-deployed periods are proportional to deployed periods.)

T_i^N can be written as:

$$T_i^N = T_i^M + T_i^{ST} + T_i^{T\&S} + T_i^{N/M} + T_i^H$$

where we have denoted:

$$T_i^M = t_D T_i^D$$ Maintenance time due to deployments

$$T_i^{ST} = \frac{d_{ST}}{Y}\left(1 + T_i^{AR}\right)T_i^D$$ Self-training time

$$T_i^{T\&S} = \frac{S}{YZ}T_i^D$$ Training & Services time

$$T_i^{N/M} = t_N\left(T_i^{ST} + T_i^{T\&S}\right)$$ Maintenance time due to non-deployed operations

$$T_i^H = hT_i^D$$ In-port time due to crew operating restrictions

We may also express the following quantities in terms of the above times:

$$P_i = \frac{T_i^D + T_i^{ST} + T_i^{T\&S}}{T_i^D + T_i^N}$$ PERSTEMPO

$$n_i = \frac{T_i^D + T_i^N}{T_i^D - T_i^{TR}}$$ Number of (available) units required to keep one on station

B. EXAMPLE: ATTACK SUBMARINE FORCE

1. Peacetime Presence Scenario

Table 1 presents the input/output for the case of an attack submarine force in the Peacetime Presence scenario. Peacetime Presence deployments are intended to provide forces in forward areas prior to a crisis and during a transition to conflict. The input characterizes four deployment stations with a total on-station requirement of eleven submarines. The operational availability (i.e. the fraction of time a unit is not in long-term overhaul) is 0.75, and two units are non-deploying. Thirty at-sea days per year of self-training are required for each unit and the total force provides 2,500 submarine-days of training and services to the rest of the Fleet. Between deployments 0.33 of the deployment time must be devoted to in-port maintenance/upkeep/supply/etc. This would be about 60 days between 180-day deployments. A similar ratio is used for maintenance activities due to out-of-port operations while non-deployed. The minimum allowed turn-around-ratio, T_0^{AR}, is 2.0 and the maximum allowed PERSTEMPO, P_0, is 0.5.

Table 1. Example: Peacetime Presence--Attack Submarine Force

INPUT

Deployment	u_i	D_i(nmi)	v_i(kts)	T_i^D(days)	$[T_i^{TR}]$*	$[Z_i]$*
#1	1	10,000	16	180	52.1	1.407
#2	3	4,000	16	180	20.8	3.392
#3	4	4,000	16	90	20.8	5.202
#4	3	4,500	16	180	23.4	3.448

n_S	A	N_R	d_{ST}(days)	S (unit-days)	t_D	t_N	T_0^{AR}	P_0	Y (days)
4	.75	2	30	2,500	.33	.33	2.0	0.5	365

OUTPUT

Z	$h(T_0^{AR})$	$h(P_0)$	h	T^{AR}
13.454	.66	1.20	1.20	2.61

Deployment	n_i	T_i^M	T_i^{ST}	$T_i^{T\&S}$	$T_i^{N/M}$	T_i^H	T_i^N	$T_i^D + T_i^N$
#1	5.1	60	53.4	91.6	48.3	216.8	470	650
#2	4.1	60	53.4	91.6	48.3	216.8	470	650
#3	4.7	30	26.7	45.8	24.2	108.4	235	325
#4	4.2	60	53.4	91.6	48.3	216.8	470	650

Force Level:

$N_{OP}^{D,T\&S}$	N(0)	$\Delta N(h(T_O^{AR}))$	$N(T_O^{AR})$	$\Delta N(h(P_O))$	$N(P_O)$	$\Delta N(h)$	N_{OP}[a]	N
30.39	42.53	10.0	55.8	18.2	66.8	18.2	48.6	66.8

* Output

[a] $N_{OP} \equiv N_{OP}^{D,T\&S} + \Delta N(h)$

The results indicate that a force of 67 attack submarines would be required under these conditions. The driving factor is P_0. If there were no restrictions on T_i^{AR} or P_i then 43 submarines would suffice $N(0) = [(30.39/.75) + 2]$. If only T_i^{AR} were restricted (= 2) then 13 units would be added $(10.0/.75 = 13.3)$. However the restriction on P_i adds a requirement of 24 units to the force $(18.2/.75 = 24.3)$.

The results for the deployment cycle are also given in Table 1. In order to satisfy all requirements, a 180-day deployment is followed by a 470-day non-deployed period for a total cycle length of 650 days (~21 months). The non-deployed period is composed of 60 days of deployment-related maintenance and upkeep, 53 days of self-training, 92 days of T&S, and 48 days of maintenance as a result of the non-deployed operations. A total of 217 in-port days per cycle is attributed to the PERSTEMPO restrictions.

Finally, the turn-around ratio for all deployments is 2.6, and it takes four or five operational units to keep one on station under these assumptions.

2. Conflict Scenario

The forces in a Conflict scenario are those required after a crisis (or crises) has erupted and the force transitions to a heightened state of readiness and operating tempo. We assume that the Conflict scenario encompasses a period from the onset of a crisis to the outbreak of hostilities as well as the period of hostilities. Therefore, during this period forces may be expected to rotate in and out of forward areas over many months. The number and location of stations, the missions, and times spent on station will all depend upon the specific planning scenarios. (See, for example, References 1, 2, 3 and 5, for a discussion of attack submarine usage during Conflict scenarios.) We estimate force levels for the Conflict scenario using the same method described above for Peacetime Presence but with input that reflects Conflict conditions. We illustrate this, as before, with an example summarized in worksheet form in Table 2.

Table 2. Example: Conflict Scenario--Attack Submarine Force

INPUT

Deployment	u_i	$D_i(\text{nmi})$	$v_i(\text{kts})$	$T_i^D(\text{days})$	$[T_i^{TR}]$*	$[Z_i]$*
#1	14	4,000	25	60	13.3	18.00
#2	7	5,000	25	75	16.7	9.00
#3	4	4,000	25	90	13.3	4.70

n_S	A	N_R	$d_{ST}(\text{days})$	S (unit-days)	t_D	t_N	T_0^{AR}	P_0	Y (days)
3	.75	0	0	1,000	.25	.25	0	.8	365

OUTPUT

Z	$h(T_0^{AR})$	$h(P_0)$	h	T^{AR}
31.70	0	0	0	.36

Deployment	n_i	T_i^M	T_i^{ST}	$T_i^{T\&S}$	$T_i^{N/M}$	T_i^H	T_i^N	$T_i^D + T_i^N$
#1	1.75	15.0	0	5.2	1.3	0	21.6	81.6
#2	1.75	18.8	0	6.5	1.6	0	27.0	102.0
#3	1.60	22.5	0	7.8	1.9	0	32.4	122.4

Force Level:

$N_{OP}^{D,T\&S}$	$N(0)$	$\Delta N(h(T_O^{AR}))$	$N(T_O^{AR})$	$\Delta N(h(P_O))$	$N(P_O)$	$\Delta N(h)$	N_{OP}[a]	N
43.0	57.4	0	57.4	0	57.4	0	43.0	57.4

* Output

[a] $N_{OP} \equiv N_{OP}^{D,T\&S} + \Delta N(h)$

In the example there are 25 submarines deployed to three areas characterized by the distances shown. The transit speeds are assumed to be higher than the Peacetime example and the on-station periods are generally shorter. The availability is assumed to be the same with 75 percent of the force not in overhaul or long-term maintenance. We assume the units that are non-deploying in Peacetime deploy in wartime ($N_R = 0$) and that self-training is reduced to those periods where other missions are being carried out $(d_{ST} = 0)$. We also assume that T&S is reduced from 2,500 submarine-days per year in Peacetime to 1,000 submarine-days per year in wartime. In addition, we assume a slightly lower percentage of operating time for in-port maintenance/upkeep (25 percent). Finally, there is no restriction on turn-around ratio and the PERSTEMPO ceiling is significantly increased $(P_0 = 0.8 \text{ vice } 0.5)$.

From the output in Table 2 we see that the restriction on PERSTEMPO has no effect on force level in this case. A total force of 57 submarines is indicated. The deployment cycles are much shorter than in the Peacetime case because: deployment times are shorter, there are no crew restrictions, and there is a reduced demand for training and services.

If the input in Tables 1 and 2 characterized actual planning scenarios then the resultant force level would be driven by the Peacetime Presence requirements.

3. Surge Scenario

Unlike the previous two cases, a "Surge" scenario does not involve the steady-state rotation of units through stations. Rather, it is a "one-shot deal." All units that are not in long-term overhaul could, in principle, be "surged." Therefore the total force necessary to surge N_S units is

$$N = \frac{1}{A} N_S \qquad (1)$$

where A is the fraction of the force that is available at any given time. For example, the submarine forces described in the above two scenarios could surge (.75)(67) = 50 and (.75)(57) = 42 units, respectively. See Reference 6 for a detailed analysis of a "Surge" scenario.

4. Combining Scenarios

We have described three scenarios that may be used to size a naval force. Of course only a single force will be procured to address all three. Therefore questions of independence and redundancy must be considered. In general, one can imagine a force deployed for Peacetime Presence suddenly facing a crisis and onset of hostilities that, first, may require a surge capability for a specific set of missions followed by a transition to a steady-state Conflict scenario. Force planners must consider the dynamics of any planning scenario in order to assess the impact of one phase on the next. At the simplest level one may separate the Peacetime scenario from the two warfighting scenarios, and combine the latter two by first requiring sufficient numbers for the surge and then transitioning the force to a steady-state Conflict scenario, taking into account potential losses during the Surge phase and the required timing of the transition. In any case, the three scenarios described above may serve as the building blocks for arriving at a final force level.

C. COSTS

We measure the cost of a force in terms of its annualized life-cycle cost:

$$C_{FORCE} = N\, C_S \quad (\$) \tag{2}$$

where N is the number of units (ships) in the (homogeneous) force, and

$$C_S = \left(C_{PROC} / L\right) + C_{O\&S\text{-}M} + C_M \qquad (\$) \tag{3}$$

where

C_{PROC}: Procurement cost ($)

L: Expected lifetime of a unit (years)

$C_{O\&S-M}$: Annual operating and support costs not counting manpower costs ($)

C_M: Annual manpower cost ($)

Of course all of the usual subtleties must be addressed in assigning costs in any particular case, such as whether to add development and learning-curve costs to C_{PROC}, to what extent to include indirect costs, discounting, etc. And we shall not explore such details further here. However, we do stress that we have explicitly separated the ship-driven O&S costs from the manpower-driven costs. This will enable us to explore tradeoffs between ship and manpower requirements. (See example below.) For simplicity we consider a homogeneous force, that is, one composed of only one type of unit. For a mixed force, the right-hand side of Equation 2 would have to be replaced by a sum over different types of units. Similar generalizations would also have to be made in the force-level model described above.

1. Example

The example of the Peacetime Presence force resulted in a total of 67 units. The annualized life-cycle cost of this force follows from Equations 2 and 3:

$$C_{FORCE} = (67)\left[\left({}^{900}/_{30}\right) + 31.4 + 5.9\right]$$

$$= 4{,}509\ (\$M) \tag{4}$$

where we have assumed ($FY-94) (Reference 1)

C_{PROC} = \$900 M

L = 30 years

$C_{O\&S-M}$ = \$31.4 M

C_M = \$5.9 M

D. APPLICATION: MULTIPLE CREWING

In the above examples for an attack submarine force the Peacetime Presence scenario dominates, and the size of the force is driven by PERSTEMPO requirements. One possibility for mitigating the effects of such requirements is to have more than one crew per submarine. While, as before, we cannot explore here important details of this issue, we use this example to illustrate how the model could be applied to such questions.

1. Effect on Force Size

The introduction of multiple crews will affect the force level model through the personnel restrictions, T_0^{AR} and P_0, and through the self-training requirement, d_{ST}. Suppose we have n_C crews per submarine, where n_C is not necessarily an integer. If each crew has a restriction on its turn-around ratio of T_0^{AR} then the effective restriction on the submarine is (see Appendix B):

$$T_{EFF}^{AR}\left(n_C\right) = \frac{T_0^{AR} + 1 - n_C}{n_C} \tag{5}$$

For example, if $T_0^{AR} = 2$ for each of two crews then $T_{EFF}^{AR} = 0.5$, and each submarine could deploy 12 out of 18 months.

Similarly, if each crew has a restriction on its PERSTEMPO, P_0, then the effective restriction on the submarine is (see Appendix B):

$$P_{EFF}\left(n_C\right) = n_C\, P_0 \qquad (6)$$

For example, if $P_0 = 0.5$ for each of two crews then $P_{EFF} = 1$, and there is no operating restriction on the submarine due to PERSTEMPO constraints.

Finally, if there is more than one crew per submarine, then that unit may have to devote more at-sea days per year to self-training. Although the exact amount will depend on the availability and quality of shore-based training facilities, in the extreme case we may assume that the total number is proportional to the number of crews per unit:

$$d_{ST}^{EFF} = d_{ST}\, n_C \qquad \text{(days)} \qquad (7)$$

where d_{ST} is the number of at-sea days per unit per year dedicated to self-training when there is only a single crew.

The impact of multiple crews on total force level can now be calculated as, for example, in Table 1 by substituting T_{EFF}^{AR}, P_{EFF}, and d_{ST}^{EFF} for T_0^{AR}, P_0 and d_{ST}, respectively.

2. Effect on Cost

When multiple crews are introduced, additional types of costs may also enter, such as the cost of shore-based training facilities to maintain readiness while no submarine is available to a crew, or the increased maintenance costs associated with an increased OPTEMPO which, in the case of nuclear submarines, may also require an additional refueling or early retirement. In the example presented here we only crudely estimate such costs, no detailed analysis is presented.

We modify the input in the example given in Equation 4 as follows:

$$C_{PROC} = 900 \text{ (\$M)}$$

$$L = 30 \text{ (years)}$$

$$C'_{O\&S\text{-}M} = 31.4\, n_C \quad \text{(\$M)} \qquad (8)$$

$$C'_M = 5.9\, n_C \quad (\$M) \qquad (9)$$

where C_{PROC} and L are the same as before, $C_{O\&S-M}$ is multiplied by the ratio of the number of operating days per year with n_C crews to that for a single crew, (which turns out to be n_C for the cases of interest here), and C_M is multiplied by the number of crews. The force cost for the multiple-crew case is then given by Equations 2 and 3:

$$C'_{FORCE} = N'\left[\left(C_{PROC} / L\right) + C'_{O\&S\text{-}M} + C'_M \right] \qquad (10)$$

where N' is the force level with T^{AR}_{EFF}, P_{EFF} and $d^{EFF'}_{ST}$ as input. Thus, the cost of a force that provides the same deployments and T&S as described in Table 1 can be determined as a function of n_C. The results are shown in Figure 1.

We see from Figure 1 that the cost decreases as the number of crews per submarine is increased from 1. This is because additional crews allow each submarine to be operated more, and crews are considerably less expensive than submarines. The cost of the force is minimized when there are about three crews for every two submarines. The savings in that case would be about $610M per year (14%) over the single crew case with no loss of deployments, maintenance or services. Over the same range the size of the force drops by about 22 units. (The total number of crews remains roughly the same.)

As the number of crews per submarine continues to increase, however, the savings over the single-crew case begin to erode. This is because the PERSTEMPO and T^{AR} constraints no longer have an impact on force size and the number of units bottoms out at about 45. By the time the case of two crews per submarine is reached, the total cost has increased over the single crew case by about $548M per year (12%) despite a force reduction of 19 units.

The above example is intended to illustrate the kind of issues that can be addressed by the methods described here. Any conclusions on force levels would have to be supported by a careful scrutiny of the underlying input.

A number of related issues with regard to the surface ship force are discussed in a recent series of CNA studies (References 8,9,10).

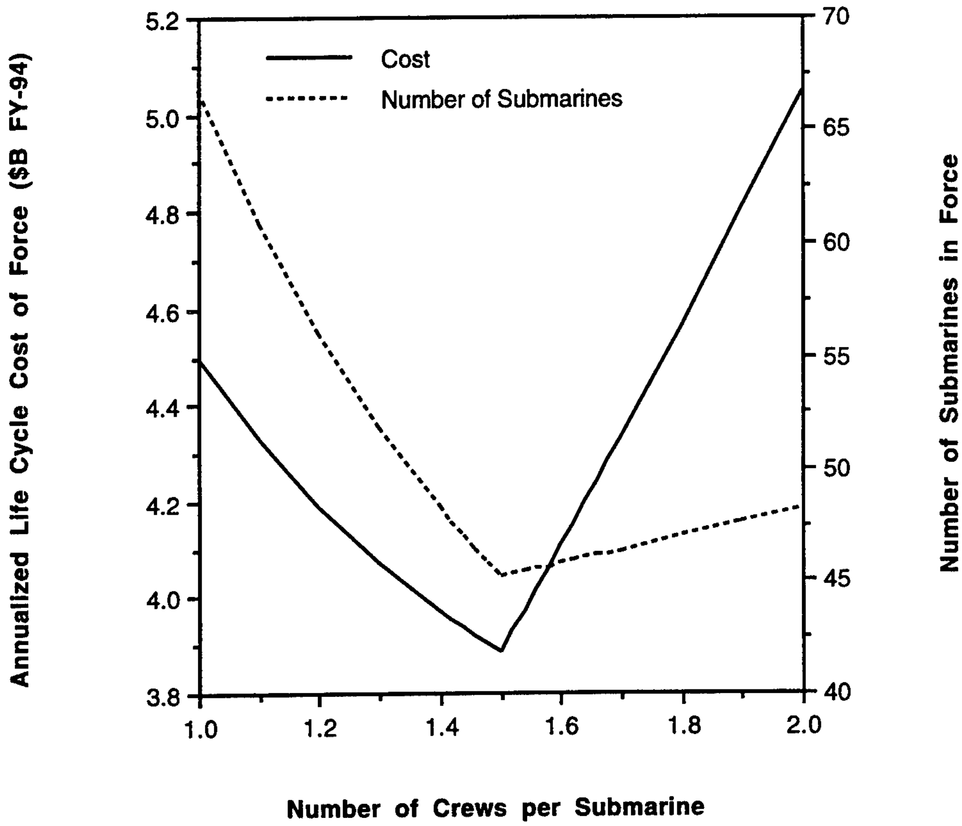

Figure 1. Illustrative Example: Cost of Submarine Force That Meets Deployment and T&S Requirements vs. Number of Crews Per Submarine

E. DISCUSSION

The above examples illustrate how the model may be used to address submarine force level issues. Analogous issues for other naval forces such as surface escorts, amphibious ships or aircraft carriers may be addressed in the same way. Also, other potential methods of reducing costs, such as forward home-porting, can be explored using this approach.

We emphasize that the above examples are only illustrative. They serve only to show how force levels and costs may be determined given the tasks assigned to the force and restrictions on its operations.

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III. DERIVATIONS

This chapter presents the definitions, assumptions and derivations that underlie the model summarized in Chapter II. We go through the worksheet shown, for example, in Table 1, and discuss each term. In the following "•" denotes input and "--" denotes quantities calculated from previous input.

A. DEPLOYMENT REQUIREMENTS

Deployment requirements are characterized by:

- n_S: Total number of locations (stations, deployment points) to be manned.
- u_i: Number of units simultaneously required at the i^{th} station. May be integer or non-integer. For example, $u_i = 0.5$ means that the i^{th} station is to be manned 6 months per year.
- D_i: One-way transit distance from home port to i^{th} station (in nmi).
- v_i: Average speed of advance during transit (in knots).
- T_i^D: Total deployment time (including transits) for a given unit deploying to the i^{th} deployment point (in days).

-- T_i^{TR}: Two-way transit time (in days) between home port and the i^{th} station:

$$T_i^{TR} = \frac{2\,D_i}{24\,v_i} \quad \text{(days)} \tag{11}$$

-- Z_i: A useful intermediate quantity defined by

$$Z_i = \frac{u_i}{1 - T_i^{TR} / T_i^D}\ , \quad Z = \sum_{i=1}^{n_S} Z_i \tag{12}$$

(The term Z_i is the number of units required to man the i^{th} station if in-port turn-around were instantaneous.)

B. OTHER INPUT PARAMETERS

- n_S: See above.
- A: Availability, the fraction of the force that is not in overhaul or long-term maintenance at any given time.
- N_R: Number of units that are not in the deployment cycle and may serve unique purposes such as R&D.
- d_{ST}: Number of days per unit per year dedicated to self-training. These days are out-of-port operating days during non-deployed periods.

In general, the requirement for self-training is given in terms of the number of self-training days away from home port required per unit per year, t_S, and the fraction of those days that cannot be achieved while performing other missions, f_S. Therefore the total number of days away from home port dedicated to self training per year, d_{ST}, is $d_{ST} = t_S f_S$.

- S: Total number of unit-days of training and services (T&S) provided by the force per year. These are days operating away from home port during non-deployed periods. S does not include self-training.
- t_D: Constant of proportionality yielding the time required in port between deployments for unit maintenance as a function of deployment time.

During each deployment cycle we assume that

$$T_i^M = t_D T_i^D \quad \text{(days)} \tag{13}$$

days of in-port maintenance are required on the unit as a result of the deployed operations. T_i^M includes both post-deployment and pre-deployment maintenance (including upkeep, supply, inspection, etc.). For simplicity we have assumed that t_D is independent of i, that is, that the in-port maintenance period depends only on the duration of the deployment and is proportional to it. If this approximation is not uniformly appropriate for all deployments considered, a breakdown into parallel forces with different deployment characteristics may be necessary. However, for most purposes for which this model is intended, the simpler version should suffice.

Note that T_i^M is due solely to required maintenance on the ship itself and not to crew-related needs such as PERSTEMPO restrictions. In practice both unit maintenance and crew in-port days occur simultaneously. This model attempts to identify the time spent in port that would be required for unit maintenance if there were no PERSTEMPO constraints from the time spent in port to explicitly satisfy PERSTEMPO constraints.

- t_N: Constant of proportionality yielding the time required in port between non-deployed operations for unit maintenance as a function of the duration of the non-deployed operations.

During each deployment cycle $T_i^{ST} + T_i^{T\&S}$ days of non-deployed operations are conducted away from home port to provide self-training $\left(T_i^{ST}\right)$ and training and services (T&S) to the Fleet $\left(T_i^{T\&S}\right)$. As a result of those operations $T_i^{N/M}$ days of in-port maintenance are required during each cycle.

As above, we assume,

$$T_i^{N/M} = t_N \left(T_i^{ST} + T_i^{T\&S}\right) \quad \text{(days)} \tag{14}$$

that is, that the amount of such maintenance is independent of i and is directly proportional to the duration of the non-deployed operations.

The next two parameters characterize the constraints put on operations due to personnel policy.

- T_0^{AR}: Minimum allowed turn-around ratio.

For the i^{th} deployment, the turn-around ratio is defined as

$$T_i^{AR} = \frac{T_i^N}{T_i^D} \tag{15}$$

where T_i^D is the deployment time and T_i^N is the ("non-deployed") time between deployments. In order to assure that crew members do not spend too much time deployed, Navy policy places a bound on T_i^{AR}:

$$T_i^{AR} \geq T_0^{AR} \tag{16}$$

and current Navy (peacetime) policy is that $T_0^{AR} = 2$ (Reference 7).

- P_0: Maximum allowed PERSTEMPO.

PERSTEMPO, P_i, is the fraction of the deployment cycle that a unit spends away from home port,

$$P_i = \frac{T_i^D + T_i^{ST} + T_i^{T\&S}}{T_i^D + T_i^N} \qquad (17)$$

As with T_i^{AR}, Navy policy places a bound on PERSTEMPO:

$$P_i \le P_0 \qquad (18)$$

and current Navy (peacetime) policy is that $P_0 = 0.5$ (Reference 7).

- Y: $Y = 365$ (days per year)

C. OUTPUT: DEPLOYMENT CYCLE

In this section we describe how the output is calculated. We first focus on the "non-deployed" part of the deployment cycle, T_i^N, and discuss its various components. These are listed in Table 3, and will provide the basis for obtaining formulas for the remainder of the worksheet which are discussed later in this chapter.

We write the non-deployed time as the sum of its components:

$$T_i^N = T_i^M + T_i^{ST} + T_i^{T\&S} + T_i^{N/M} + T_i^H \quad \text{(days)} \qquad (19)$$

where we have:

-- T_i^M: The (average) number of days spent in home port between deployments for maintenance (upkeep, supply, inspection, etc.) as a result of the deployments.

T_i^M includes both post-deployment and pre-deployment periods. Equation 13 gives

$$T_i^M = t_D T_i^D \quad \text{(days)} \qquad (20)$$

which was discussed previously.

-- T_i^{ST}: The (average) number of days spent operating away from home port during the non-deployed periods that are dedicated to crew self-training.

Table 3. Formulas for Deployment Cycle Output in Worksheet

Term and Formula	Relevant Equation in Text
$Z = \sum_{i=1}^{n_S} Z_i = \sum_{i=1}^{n_S} \frac{u_i}{1 - T_i^{TR} / T_i^D}$	12
$h\left(T_0^{AR}\right) = \max \left\{0,\ T_0^{AR} - (1+t_N)\frac{d_{ST}}{Y}\left(T_0^{AR}+1\right) - \frac{S}{YZ}(1+t_N) - t_D\right\}$	39
$h(P_0) = \max\left\{0, \frac{\left(Y-(1+t_N)d_{ST}\right)\left(\frac{S}{ZY}+1\right)}{YP_0 - d_{ST}} - 1 - (1+t_N)\frac{S}{YZ} - t_D\right\}$	40
$h = \max \left\{h\left(T_0^{AR}\right),\ h(P_0)\right\}$	41
$T_{AR} = \frac{Y}{Y-(1+t_N)d_{ST}}\left(t_D + (1+t_N)\left(\frac{d_{ST}}{Y} + \frac{S}{YZ}\right) + h\right)$	37, 38
$n_i = \left(1+T^{AR}\right)\frac{Z_i}{u_i}$	27, 38, 12
$T_i^M = t_D T_i^D$	20
$T_i^{ST} = \frac{d_{ST}}{Y}\left(1+T^{AR}\right)T_i^D$	22
$T_i^{T\&S} = \frac{S}{YZ}T_i^D$	33
$T_i^{N/M} = t_N\left(T_i^{ST} + T_i^{T\&S}\right) = t_N\left(\frac{d_{ST}}{Y}\left(1+T^{AR}\right) + \frac{S}{YZ}\right)T_i^D$	35
$T_i^H = hT_i^D$	36
$T_i^N = T^{AR}T_i^D$	38

T_i^{ST} does not include self-training activities that can be performed while carrying out other missions. As discussed above (Section III-B), self-training requirements are generally expressed in terms of the total number of days away from home port per unit per year that must be dedicated to self-training. We have denoted this quantity by d_{ST}. In order to determine T_i^{ST} we note that the (average) number of deployment cycles per year is

$$\frac{Y}{T_i^D + T_i^N} \quad \text{(cycles per year)}$$

and so the number of self-training days per cycle must be

$$T_i^{ST} = \frac{d_{ST}}{Y}\left(T_i^D + T_i^N\right) \tag{21}$$

$$= \frac{d_{ST}}{Y}\left(1 + T_i^{AR}\right) T_i^D \tag{22}$$

-- $T_i^{T\&S}$: The (average) number of days spent operating away from home port during the non-deployed period that are dedicated to performing training and services (T&S) for other elements of the Fleet. Such operations may involve participation in exercises, test and evaluation activities, R&D activities, etc.

As noted above, T&S requirements are generally given in terms of the annual number of unit-days that must be provided by the total force, and we have denoted this total as S. In order to relate $T_i^{T\&S}$ to S we note that a unit deploying to the i^{th} station will deliver

$$w_i = T_i^{T\&S} \frac{Y}{T_i^D + T_i^N} \tag{23}$$

unit-days of T&S per year. Let N_i be the number of units deploying to the i^{th} station. It is given by

$$N_i = u_i n_i \tag{24}$$

where u_i, as defined above, is the number of units required to be simultaneously on station, and n_i is the number of units required to keep one on station. The term n_i is determined by noting that a single deploying unit spends the following fraction of its cycle time on station:

$$F_i^{OS} = \frac{T_i^D - T_i^{TR}}{T_i^D + T_i^N} \tag{25}$$

So n_i is given by

$$n_i = \left(F_i^{OS}\right)^{-1} \tag{26}$$

$$= \frac{T_i^D + T_i^N}{T_i^D - T_i^{TR}} \tag{27}$$

The total number of unit-days of T&S provided by units cycling to and from all the stations can now be determined from Equations 23, 24 and 27. It is

$$S = \sum_{i=1}^{n_S} N_i w_i \tag{28}$$

$$= Y \sum_{i=1}^{n_S} u_i \frac{T_i^{T\&S}}{T_i^D - T_i^{TR}} \tag{29}$$

At this point a scheduler may wish to apportion $T_i^{T\&S}$ in any way that provides a total annual output of S unit-days. However, looking ahead to constraints on T_i^{AR}, we assume that longer deployments are followed by proportionately longer non-deployed periods and therefore we take (on average) that

$$T_i^{T\&S} = c\, T_i^D \quad \text{(days)} \tag{30}$$

where c is a constant of proportionality independent of i.

Equations 29 and 30 then yield

$$S = c\, Y \sum_{i=1}^{n_S} \frac{u_i}{1 - T_i^{TR} / T_i^D} \quad \text{(unit-days)} \tag{31}$$

$$= c\, Y\, Z \quad \text{(unit-days)} \tag{32}$$

where Equation 12 has been used for Z. Equation 32 therefore determines c, and using Equation 30 we get

$$T_i^{T\&S} = \frac{S}{YZ} T_i^D \quad \text{(days)} \tag{33}$$

-- $T^{N/M}$: The (average) number of days spent in port for maintenance as a result of the non-deployed operations for self-training and T&S.

As discussed above (Equation 14), we have from Equations 21 and 33:

$$T_i^{N/M} = t_N \left(T_i^{ST} + T_i^{T\&S} \right) \quad \text{(days)} \tag{34}$$

$$= t_N \left(\frac{d_{ST}}{Y} \left(T_i^D + T_i^N \right) + \frac{S}{YZ} T_i^D \right) \quad \text{(days)} \tag{35}$$

-- T_i^H: The (average) number of days spent in home port not as a result of unit maintenance requirements but in order to meet restrictions on T^{AR} and PERSTEMPO.

As discussed previously the model requires that in-port periods be apportioned between the amount dedicated to ship maintenance and the amount dedicated to meeting crew operating constraints.

Since crew operating constraints are driven by deployment times, we assume that this additional time spent in port is proportional to T_i^D and independent of i:

$$T_i^H = h\, T_i^D \quad \text{(days)} \tag{36}$$

We now gather up the above results for the components of T_i^N and find (from Equations 19, 20, 21, 33, 35 and 36):

$$T_i^N = \left[\frac{Y}{Y - \left(1 + t_N\right) d_{ST}} \left(t_D + \left(1 + t_N\right)\left(\frac{d_{ST}}{Y} + \frac{S}{YZ} \right) + h \right) \right] T_i^D \tag{37}$$

and therefore the turn-around ratio,

$$T^{AR} = \frac{T_i^N}{T_i^D} \tag{38}$$

is independent of i.

All of the terms on the right-hand side of Equation 37 are given as input except h which must be determined from the restrictions on T^{AR} and PERSTEMPO. We now turn to this issue.

-- $h\left(T_0^{AR}\right)$: The value of h required to satisfy the constraint on T^{AR} (See Equation 16.).

We assume the minimum allowable $T^{AR} = T_0^{AR}$ and solve Equations 37 and 38 for h. The result is:

$$h\left(T_0^{AR}\right) = \max\left\{0,\ T_0^{AR} - \frac{\left(1+t_N\right)d_{ST}}{Y}\left(T_0^{AR}+1\right) - \frac{S}{YZ}\left(1+t_N\right) - t_D\right\} \qquad (39)$$

where the "max" is used to indicate that $h \geq 0$.

- -- $h(P_0)$: The value of h required to satisfy the constraint on PERSTEMPO (See Equation 18).

We assume the maximum allowable value, $P_i = P_0$, and solve Equations 17, 22, 33 and 37 for h. The result is:

$$h\left(P_0\right) = \max\left\{0,\ \frac{\left(Y - \left(1+t_N\right)d_{ST}\right)\left(\frac{S}{ZY}+1\right)}{YP_0 - d_{ST}} - 1 - \left(1+t_N\right)\frac{S}{YZ} - t_D\right\} \qquad (40)$$

If constraints on both T^{AR} and P are in effect, we must choose the greater of these two values for h. Thus we have

$$h = \max\left\{h\left(T_0^{AR}\right),\ h\left(P_0\right)\right\} \qquad (41)$$

and all of the components of the deployment cycle are now given in terms of the input. Table 3 presents the formulas for the various terms in the worksheet that result from the above considerations.

D. OUTPUT: FORCE LEVELS

We now show how the force levels follow from the above results.

The total number of deploying submarines needed to meet all of the input requirements is given by Equations 12, 24, 27 and 38:

$$N_{OP} = \sum_{i=1}^{n_s} N_i = \left(1+T^{AR}\right)Z \qquad (42)$$

and, expanding T^{AR} using Equations 37 and 38, we get

$$N_{OP} = Z + \frac{1}{Y - \left(1+t_N\right)d_{ST}}\left(YZt_D + \left(1+t_N\right)\left(d_{ST}Z+S\right)\right) + \frac{hYZ}{Y - \left(1+t_N\right)d_{ST}} \qquad (43)$$

- -- $N_{OP}^{D,T\&S}$: The number of operational units needed for deployments and T&S requirements.

If there are no T^{AR} or P constraints, h = 0 and the first two terms of Equation 43 yield $N_{OP}^{D,T\&S}$:

$$N_{OP}^{D,\,T\&S} = Z + \frac{1}{Y - \left(1 + t_N\right) d_{ST}} \left(Y Z t_D + \left(1 + t_N\right)\left(d_{ST} Z + S\right)\right) \qquad (44)$$

-- $\Delta N(h)$: Number of additional operational units required so that crew operating restrictions can be satisfied.

If there are T^{AR} and/or P constraints the additional units required are given by the last term in Equation 43:

$$\Delta N\left(h\right) = \frac{h\,Y Z}{Y - \left(1 + t_N\right) d_{ST}} \qquad (45)$$

where h is given by Equation 39 (constraint only on T^{AR}), Equation 40 (constraint only on P), or Equation 41 (constraints on both T^{AR} and P).

-- N: Total force level

The total force for each of the above constraint conditions is now given by

$$N = \frac{1}{A}\left(N_{OP}^{D,\,T\&S} + \Delta N\left(h\right)\right) + N_R \qquad (46)$$

Table 4 summarizes these results.

Table 4. Formulas for Force Level Output

Term and Formula	Relevant Equation in Text
$N_{OP}^{D,T\&S} = Z + \frac{1}{Y - (1 + t_N) d_{ST}} \left[YZt_D + (1 + t_N)(d_{ST} Z + S) \right]$	44
$N(0) = \frac{1}{A} N_{OP}^{D,T\&S} + N_R$	46
$\Delta N\left(h\left(T_0^{AR}\right)\right) = \frac{h\left(T_0^{AR}\right) YZ}{Y - (1 + t_N) d_{ST}}$	45, 39
$N\left(T_0^{AR}\right) = \frac{1}{A}\left[N_{OP}^{D,T\&S} + \Delta N\left(h\left(T_0^{AR}\right)\right)\right] + N_R$	46
$\Delta N\left(h\left(P_0\right)\right) = \frac{h\left(P_0\right) YZ}{Y - (1 + t_N) d_{ST}}$	45, 40
$N\left(P_0\right) = \frac{1}{A}\left[N_{OP}^{D,T\&S} + \Delta N\left(h\left(P_0\right)\right)\right] + N_R$	46
$\Delta N(h) = \frac{hYZ}{Y - (1 + t_N) d_{ST}}$	45, 41
$N_{OP} = N_{OP}^{D,T\&S} + \Delta N(h)$	43
$N = \frac{1}{A} N_{OP} + N_R$	46

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APPENDIX A

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Appendix A
REFERENCES

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APPENDIX B

DERIVATION OF EFFECTIVE UNIT TURN-AROUND RATIO AND EFFECTIVE UNIT PERSTEMPO WHEN A UNIT HAS MULTIPLE CREWS

Appendix B

DERIVATION OF EFFECTIVE UNIT TURN-AROUND RATIO AND EFFECTIVE UNIT PERSTEMPO WHEN A UNIT HAS MULTIPLE CREWS

1. EFFECTIVE UNIT TURN-AROUND TIME

The turn-around ratio is given by

$$T^{AR} = T^{N}/T^{D} \quad \text{(B-1)}$$

where T^D is the deployment time and T^N is the non-deployed time between deployments. When each ship (or "unit") has only one crew, T^{AR} for the unit and T^{AR} for the crew are the same, and any restrictions on the crew's T^{AR} is directly applied to the unit's T^{AR}. However, when a unit has more than one crew, we must distinguish between the two T^{AR}'s and determine the impact on unit T^{AR} due to restrictions on crew T^{AR}.

We denote unit T^{AR} as

$$T_U^{AR} = T^{N}/T^{D} \quad \text{(B-2)}$$

and crew T^{AR} as

$$T_C^{AR} = T_C^{N}/T^{D} \quad \text{(B-3)}$$

where T^D is the deployment time for a given deployment, T^N is the time between successive deployments for the unit, and T_C^N is the time between deployments for a given crew. Now if there are n_C crews per unit (n_C need not be an integer) then the time between deployments for a given crew is

$$T_C^{N} = n_C T^{N} + \left(n_C - 1\right) T^{D} \quad \text{(B-4)}$$

that is, the n_C non-deployed periods plus all of the deployed periods other than the one that that particular crew is on. Thus a crew's turn-around ratio is

$$T_C^{AR} = n_C T^{N}/T^{D} + n_C - 1 \quad \text{(B-5)}$$

and, by Equation B-2, T_U^{AR} is therefore given by

$$T_U^{AR} = \frac{T_C^{AR} + 1 - n_C}{n_C} \qquad \text{(B-6)}$$

which is Equation5 in the main text with $T_U^{AR} = T_{EFF}^{AR}\,(n_C)$ and $T_C^{AR} = T_0^{AR}$.

2. EFFECTIVE UNIT PERSTEMPO

As with T^{AR}, when there are more than one crew per unit we must distinguish between a given crew's PERSTEMPO, P_C, and a unit's "PERSTEMPO," P_U. Again assume there are n_C crews per unit. Over a given single deployment cycle we have

$$P_U = \frac{T^{AWAY}}{T^{AWAY} + T^{HOME}} \qquad \text{(B-7)}$$

where T^{AWAY} is the time spent away from home port and T^{HOME} is the time spent in home port during that single deployment cycle.

From a crew's point of view we have over n_C cycles:

$$P_C = \frac{T^{AWAY}}{n_C\left(T^{AWAY} + T^{HOME}\right)} \qquad \text{(B-8)}$$

So

$$P_U = n_C\,P_C \qquad \text{(B-9)}$$

which is Equation 6 with $P_U = P_{EFF}\,(n_C)$ and $P_C = P_0$.

APPENDIX C

SPREADSHEET VERSION OF MODEL

Appendix C
SPREADSHEET VERSION OF MODEL

In this appendix we present a spreadsheet version of the basic force level model. This may be used as is, or it may serve as a starting point to be modified to focus on different aspects of force level issues. Excel files containing these worksheets are available on disk from the author [(703) 845-2415, Fax: (703) 845-6722, E-Mail: whurley@ida.org].

The Excel worksheet corresponding to Table 1 is given in Table C-1, and the underlying formulas are listed in Tables C-2-A through C-2-F. Tables C-3 and C-4-A through C-4-F give the analogous spreadsheets when costs are included, as in Chapter II, section C of the main text.

Table C-1. Excel Spreadsheet Results for Peacetime Presence Scenario

	A	B	C	D	E	F	G	H	I
1	FORCE LEVEL								
2	INPUT						(* output)		
3	DEPLOYMENT	u(i)	D(i) (nmi)	v(i) (kts)	T^D(i) (d)		[T^TR(i)]*	[z(i)]*	
4	#1	1.00	10,000.00	16.00	180.00		52.08	1.41	
5	#2	3.00	4,000.00	16.00	180.00		20.83	3.39	
6	#3	4.00	4,000.00	16.00	90.00		20.83	5.20	
7	#4	3.00	4,500.00	16.00	180.00		23.44	3.45	
8	#5						0.00	0.00	
9	#6						0.00	0.00	
10	#7						0.00	0.00	
11	#8						0.00	0.00	
12	#9						0.00	0.00	
13	#10						0.00	0.00	
14	PARAMETER	n(s)	A	N(R)	d(ST) (d)	S (unit-d)	t(D)	t(N)	TAR/0
15		4.00	0.75	2.00	30.00	2,500.00	0.33	0.33	2.00
16		P/0	Y						
17		0.50	365						
18									
19	OUTPUT								
20	PARAMETER	Z	h(TAR/0)	h(P/0)	h	TAR			
21		13.45	0.66	1.20	1.20	2.61			
22	DEPLOYMENT	n(i)	T^M(i)	T^ST(i)	T^T&S(i)	T^N/M(i)	T^H(i)	T^N(i)	T^D+N(i)
23	#1	5.08	59.94	53.44	91.64	48.31	216.83	470.15	650.15
24	#2	4.08	59.94	53.44	91.64	48.31	216.83	470.15	650.15
25	#3	4.70	29.97	26.72	45.82	24.16	108.41	235.08	325.08
26	#4	4.15	59.94	53.44	91.64	48.31	216.83	470.15	650.15
27	#5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
28	#6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
29	#7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	#8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
31	#9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
32	#10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
33	FORCE LEVEL		N(0)	DN/TAR/0	N(TAR/0)	DN/P/0	N(P/0)	DN(h)	N(OP)
34	N(D,T&S/OP)	30.39	42.53	9.97	55.82	18.20	66.79	18.20	48.59
35	N	66.79							

Table C-2-A. Excel Spreadsheet Formulation of Force Level Model

	A	B
1	FORCE LEVEL	
2	INPUT	
3	DEPLOYMENT	u(i)
4	#1	1
5	#2	3
6	#3	4
7	#4	3
8	#5	
9	#6	
10	#7	
11	#8	
12	#9	
13	#10	
14	PARAMETER	n(s)
15		4
16		P/0
17		0.5
18		
19	OUTPUT	
20	PARAMETER	Z
21		=SUM(H4:H13)
22	DEPLOYMENT	n(i)
23	#1	=IF(B4=0,0,(1+F21)*H4/B4)
24	#2	=IF(B5=0,0,(1+F21)*H5/B5)
25	#3	=IF(B6=0,0,(1+F21)*H6/B6)
26	#4	=IF(B7=0,0,(1+F21)*H7/B7)
27	#5	=IF(B8=0,0,(1+F21)*H8/B8)
28	#6	=IF(B9=0,0,(1+F21)*H9/B9)
29	#7	=IF(B10=0,0,(1+F21)*H10/B10)
30	#8	=IF(B11=0,0,(1+F21)*H11/B11)
31	#9	=IF(B12=0,0,(1+F21)*H12/B12)
32	#10	=IF(B13=0,0,(1+F21)*H13/B13)
33	FORCE LEVEL	
34	N(D,T&S/OP)	=B21+(C17*B21*G15+(1+H15)*(E15*B21+F15))/(C17-(1+H15)*E15)
35	N	=(I34/C15)+D15

Table C-2-B. Excel Spreadsheet Formulation of Force Level Model (Cont'd.)

	C
1	
2	
3	D(i) (nmi)
4	10000
5	4000
6	4000
7	4500
8	
9	
10	
11	
12	
13	
14	A
15	0.75
16	Y
17	365
18	
19	
20	h(TAR/0)
21	= MAX(0,I15-(1+H15)*E15*(I15+1)/C17-F15*(H15+1)/(C17*B21)-G15)
22	T^M(i)
23	=$G$15*E4
24	=$G$15*E5
25	=$G$15*E6
26	=$G$15*E7
27	=$G$15*E8
28	=$G$15*E9
29	=$G$15*E10
30	=$G$15*E11
31	=$G$15*E12
32	=$G$15*E13
33	N(0)
34	=(B34/C15)+D15
35	

Table C-2-C. Excel Spreadsheet Formulation of Force Level Model (Cont'd.)

	D
1	
2	
3	v(i) (kts)
4	16
5	16
6	16
7	16
8	
9	
10	
11	
12	
13	
14	N(R)
15	2
16	
17	
18	
19	
20	h(P/0)
21	=MAX(0,((C17-(1+H15)*E15)*(1+F15/(B21*C17))/(C17*B17-E15))-1-(1+H15)*F15/(C17*B21)-G15)
22	T^ST(i)
23	=$E$15*(1+$F$21)*E4/$C$17
24	=$E$15*(1+$F$21)*E5/$C$17
25	=$E$15*(1+$F$21)*E6/$C$17
26	=$E$15*(1+$F$21)*E7/$C$17
27	=$E$15*(1+$F$21)*E8/$C$17
28	=$E$15*(1+$F$21)*E9/$C$17
29	=$E$15*(1+$F$21)*E10/$C$17
30	=$E$15*(1+$F$21)*E11/$C$17
31	=$E$15*(1+$F$21)*E12/$C$17
32	=$E$15*(1+$F$21)*E13/$C$17
33	DN/TAR/0
34	=C21*C17*B21/(C17-(1+H15)*E15)
35	

Table C-2-D. Excel Spreadsheet Formulation of Force Level Model (Cont'd.)

	E
1	
2	
3	T^D(i) (d)
4	180
5	180
6	90
7	180
8	
9	
10	
11	
12	
13	
14	d(ST) (d)
15	30
16	
17	
18	
19	
20	h
21	=MAX(C21,D21)
22	T^T&S(i)
23	=$F$15*E4/($C$17*$B$21)
24	=$F$15*E5/($C$17*$B$21)
25	=$F$15*E6/($C$17*$B$21)
26	=$F$15*E7/($C$17*$B$21)
27	=$F$15*E8/($C$17*$B$21)
28	=$F$15*E9/($C$17*$B$21)
29	=$F$15*E10/($C$17*$B$21)
30	=$F$15*E11/($C$17*$B$21)
31	=$F$15*E12/($C$17*$B$21)
32	=$F$15*E13/($C$17*$B$21)
33	N(TAR/0)
34	=((B34+D34)/C15)+D15
35	

Table C-2-E. Excel Spreadsheet Formulation of Force Level Model (Cont'd.)

	F
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	S (unit-d)
15	2500
16	
17	
18	
19	
20	TAR
21	=(C17/(C17-(1+H15)*E15))*(G15+(1+H15)*((E15/C17)+F15/(C17*B21))+E21)
22	T^N/M(i)
23	=$H$15*(D23+E23)
24	=$H$15*(D24+E24)
25	=$H$15*(D25+E25)
26	=$H$15*(D26+E26)
27	=$H$15*(D27+E27)
28	=$H$15*(D28+E28)
29	=$H$15*(D29+E29)
30	=$H$15*(D30+E30)
31	=$H$15*(D31+E31)
32	=$H$15*(D32+E32)
33	DN/P/0
34	=D21*C17*B21/(C17-(1+H15)*E15)
35	

Table C-2-F. Excel Spreadsheet Formulation of Force Level Model (Cont'd.)

	G	H	I
1			
2	(* output)		
3	[T^TR(i)]*	[z(i)]*	
4	=IF(D4=0,0,C4/(12*D4))	=IF(E4=0,0,B4/(1-G4/E4))	
5	=IF(D5=0,0,C5/(12*D5))	=IF(E5=0,0,B5/(1-G5/E5))	
6	=IF(D6=0,0,C6/(12*D6))	=IF(E6=0,0,B6/(1-G6/E6))	
7	=IF(D7=0,0,C7/(12*D7))	=IF(E7=0,0,B7/(1-G7/E7))	
8	=IF(D8=0,0,C8/(12*D8))	=IF(E8=0,0,B8/(1-G8/E8))	
9	=IF(D9=0,0,C9/(12*D9))	=IF(E9=0,0,B9/(1-G9/E9))	
10	=IF(D10=0,0,C10/(12*D10))	=IF(E10=0,0,B10/(1-G10/E10))	
11	=IF(D11=0,0,C11/(12*D11))	=IF(E11=0,0,B11/(1-G11/E11))	
12	=IF(D12=0,0,C12/(12*D12))	=IF(E12=0,0,B12/(1-G12/E12))	
13	=IF(D13=0,0,C13/(12*D13))	=IF(E13=0,0,B13/(1-G13/E13))	
14	t(D)	t(N)	TAR/0
15	0.333	0.333	2
16			
17			
18			
19			
20			
21			
22	T^H(i)	T^N(i)	T^D+N(i)
23	=$E$21*E4	=$F$21*E4	=H23+E4
24	=$E$21*E5	=$F$21*E5	=H24+E5
25	=$E$21*E6	=$F$21*E6	=H25+E6
26	=$E$21*E7	=$F$21*E7	=H26+E7
27	=$E$21*E8	=$F$21*E8	=H27+E8
28	=$E$21*E9	=$F$21*E9	=H28+E9
29	=$E$21*E10	=$F$21*E10	=H29+E10
30	=$E$21*E11	=$F$21*E11	=H30+E11
31	=$E$21*E12	=$F$21*E12	=H31+E12
32	=$E$21*E13	=$F$21*E13	=H32+E13
33	N(P/0)	DN(h)	N(OP)
34	=((B34+F34)/C15)+D15	=MAX(D34,F34)	=B34+H34
35			

Table C-3. Excel Spreadsheet Results for Peacetime Presence Scenario When Costs Are Included

	A	B	C	D	E	F	G	H	I
1	FORCE LEVEL								
2	INPUT						(* output)		COST INP
3	DEPLOYMENT	u(i)	D(i) (nmi)	v(i) (kts)	T^D(i) (d)		[T^TR(i)]*	[z(i)]*	n(C)
4	#1	1.00	10,000.00	16.00	180.00		52.08	1.41	1.00
5	#2	3.00	4,000.00	16.00	180.00		20.83	3.39	TAR/0
6	#3	4.00	4,000.00	16.00	90.00		20.83	5.20	2.00
7	#4	3.00	4,500.00	16.00	180.00		23.44	3.45	P/0
8	#5						0.00	0.00	0.50
9	#6						0.00	0.00	C(PROC)
10	#7						0.00	0.00	900.00
11	#8						0.00	0.00	L
12	#9						0.00	0.00	30.00
13	#10						0.00	0.00	
14	PARAMETER	n(s)	A	N(R)	d(ST) (d)	S (unit-d)	t(D)	t(N)	TAR/n(C)*
15		4.00	0.75	2.00	30.00	2,500.00	0.33	0.33	2.00
16		P/n(C)*	Y	d(ST)/n(c)*					C(O&S-M)
17		0.50	365	30.00					31.40
18									C(M)
19	OUTPUT								5.90
20	PARAMETER	Z	h(TAR/0)	h(P/0)	h	TAR			
21		13.45	0.66	1.20	1.20	2.61			
22	DEPLOYMENT	n(i)	T^M(i)	T^ST(i)	T^T&S(i)	T^N/M(i)	T^H(i)	T^N(i)	T^D+N(i)
23	#1	5.08	59.94	53.44	91.64	48.31	216.83	470.15	650.15
24	#2	4.08	59.94	53.44	91.64	48.31	216.83	470.15	650.15
25	#3	4.70	29.97	26.72	45.82	24.16	108.41	235.08	325.08
26	#4	4.15	59.94	53.44	91.64	48.31	216.83	470.15	650.15
27	#5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
28	#6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
29	#7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	#8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
31	#9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
32	#10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
33	FORCE LEVEL		N(0)	DN/TAR/0	N(TAR/0)	DN/P/0	N(P/0)	DN(h)	N(OP)
34	N(D,T&S/OP)	30.39	42.53	9.97	55.82	18.20	66.79	18.20	48.59
35	N	66.79							
36	COST ($M/yr)								
37	C	4,495.12							

Table C-4-A. Excel Spreadsheet Formulation of Force Level Model Including Costs

	A	B
1	FORCE LEVEL	
2	INPUT	
3	DEPLOYMENT	u(i)
4	#1	1
5	#2	3
6	#3	4
7	#4	3
8	#5	
9	#6	
10	#7	
11	#8	
12	#9	
13	#10	
14	PARAMETER	n(s)
15		4
16		P/n(C)*
17		=I4*I8
18		
19	OUTPUT	
20	PARAMETER	Z
21		=SUM(H4:H13)
22	DEPLOYMENT	n(i)
23	#1	=IF(B4=0,0,(1+F21)*H4/B4)
24	#2	=IF(B5=0,0,(1+F21)*H5/B5)
25	#3	=IF(B6=0,0,(1+F21)*H6/B6)
26	#4	=IF(B7=0,0,(1+F21)*H7/B7)
27	#5	=IF(B8=0,0,(1+F21)*H8/B8)
28	#6	=IF(B9=0,0,(1+F21)*H9/B9)
29	#7	=IF(B10=0,0,(1+F21)*H10/B10)
30	#8	=IF(B11=0,0,(1+F21)*H11/B11)
31	#9	=IF(B12=0,0,(1+F21)*H12/B12)
32	#10	=IF(B13=0,0,(1+F21)*H13/B13)
33	FORCE LEVEL	
34	N(D,T&S/OP)	=B21+(C17*B21*G15+(1+H15)*(D17*B21+F15))/(C17-(1+H15)*D17)
35	N	=(I34/C15)+D15
36	COST ($M/yr)	
37	C	=B35*((I10/I12)+I17*I4+I19*I4)

Table C-4-B. Excel Spreadsheet Formulation of Force Level Model Including Costs (Cont'd.)

	C
1	
2	
3	D(i) (nmi)
4	10000
5	4000
6	4000
7	4500
8	
9	
10	
11	
12	
13	
14	A
15	0.75
16	Y
17	365
18	
19	
20	h(TAR/0)
21	= MAX(0,I15-(1 +H15)*D17*(I15+1)/C17-F15*(H15+1)/(C17*B21)-G15)
22	T^M(i)
23	=$G$15*E4
24	=$G$15*E5
25	=$G$15*E6
26	=$G$15*E7
27	=$G$15*E8
28	=$G$15*E9
29	=$G$15*E10
30	=$G$15*E11
31	=$G$15*E12
32	=$G$15*E13
33	N(0)
34	=(B34/C15)+D15
35	
36	
37	

Table C-4-C. Excel Spreadsheet Formulation of Force Level Model Including Costs (Cont'd.)

	D
1	
2	
3	v(i) (kts)
4	16
5	16
6	16
7	16
8	
9	
10	
11	
12	
13	
14	N(R)
15	2
16	d(ST)/n(c)*
17	=E15*I4
18	
19	
20	h(P/0)
21	=MAX(0,((C17-(1+H15)*D17)*(1+F15/(B21*C17))/(C17*B17-D17))-1-(1+H15)*F15/(C17*B21)-G15)
22	T^ST(i)
23	=$D$17*(1+$F$21)*E4/$C$17
24	=$D$17*(1+$F$21)*E5/$C$17
25	=$D$17*(1+$F$21)*E6/$C$17
26	=$D$17*(1+$F$21)*E7/$C$17
27	=$D$17*(1+$F$21)*E8/$C$17
28	=$D$17*(1+$F$21)*E9/$C$17
29	=$D$17*(1+$F$21)*E10/$C$17
30	=$D$17*(1+$F$21)*E11/$C$17
31	=$D$17*(1+$F$21)*E12/$C$17
32	=$D$17*(1+$F$21)*E13/$C$17
33	DN/TAR/0
34	=C21*C17*B21/(C17-(1+H15)*D17)
35	
36	
37	

Table C-4-D. Excel Spreadsheet Formulation of Force Level Model Including Costs (Cont'd.)

	E
1	
2	
3	T^D(i) (d)
4	180
5	180
6	90
7	180
8	
9	
10	
11	
12	
13	
14	d(ST) (d)
15	30
16	
17	
18	
19	
20	h
21	=MAX(C21,D21)
22	T^T&S(i)
23	=$F$15*E4/($C$17*$B$21)
24	=$F$15*E5/($C$17*$B$21)
25	=$F$15*E6/($C$17*$B$21)
26	=$F$15*E7/($C$17*$B$21)
27	=$F$15*E8/($C$17*$B$21)
28	=$F$15*E9/($C$17*$B$21)
29	=$F$15*E10/($C$17*$B$21)
30	=$F$15*E11/($C$17*$B$21)
31	=$F$15*E12/($C$17*$B$21)
32	=$F$15*E13/($C$17*$B$21)
33	N(TAR/0)
34	=((B34+D34)/C15)+D15
35	
36	
37	

Table C-4-E. Excel Spreadsheet Formulation of Force Level Model Including Costs (Cont'd.)

	F
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	S (unit-d)
15	2500
16	
17	
18	
19	
20	TAR
21	=(C17/(C17-(1+H15)*D17))*(G15+(1+H15)*((D17/C17)+F15/(C17*B21))+E2)
22	T^N/M(i)
23	=$H$15*(D23+E23)
24	=$H$15*(D24+E24)
25	=$H$15*(D25+E25)
26	=$H$15*(D26+E26)
27	=$H$15*(D27+E27)
28	=$H$15*(D28+E28)
29	=$H$15*(D29+E29)
30	=$H$15*(D30+E30)
31	=$H$15*(D31+E31)
32	=$H$15*(D32+E32)
33	DN/P/0
34	=D21*C17*B21/(C17-(1+H15)*D17)
35	
36	
37	

Table C-4-F. Excel Spreadsheet Formulation of Force Level Model Including Costs (Cont'd.)

	G	H	I
1			
2	(* output)		COST INP
3	[T^TR(i)]*	[z(i)]*	n(C)
4	=IF(D4=0,0,C4/(12*D4))	=IF(E4=0,0,B4/(1-G4/E4))	1
5	=IF(D5=0,0,C5/(12*D5))	=IF(E5=0,0,B5/(1-G5/E5))	TAR/0
6	=IF(D6=0,0,C6/(12*D6))	=IF(E6=0,0,B6/(1-G6/E6))	2
7	=IF(D7=0,0,C7/(12*D7))	=IF(E7=0,0,B7/(1-G7/E7))	P/0
8	=IF(D8=0,0,C8/(12*D8))	=IF(E8=0,0,B8/(1-G8/E8))	0.5
9	=IF(D9=0,0,C9/(12*D9))	=IF(E9=0,0,B9/(1-G9/E9))	C(PROC)
10	=IF(D10=0,0,C10/(12*D10))	=IF(E10=0,0,B10/(1-G10/E10))	900
11	=IF(D11=0,0,C11/(12*D11))	=IF(E11=0,0,B11/(1-G11/E11))	L
12	=IF(D12=0,0,C12/(12*D12))	=IF(E12=0,0,B12/(1-G12/E12))	30
13	=IF(D13=0,0,C13/(12*D13))	=IF(E13=0,0,B13/(1-G13/E13))	
14	t(D)	t(N)	TAR/n(C)*
15	0.333	0.333	=(1+I6-I4)/I4
16			C(O&S-M)
17			31.4
18			C(M)
19			5.9
20			
21			
22	T^H(i)	T^N(i)	T^D+N(i)
23	=$E$21*E4	=$F$21*E4	=H23+E4
24	=$E$21*E5	=$F$21*E5	=H24+E5
25	=$E$21*E6	=$F$21*E6	=H25+E6
26	=$E$21*E7	=$F$21*E7	=H26+E7
27	=$E$21*E8	=$F$21*E8	=H27+E8
28	=$E$21*E9	=$F$21*E9	=H28+E9
29	=$E$21*E10	=$F$21*E10	=H29+E10
30	=$E$21*E11	=$F$21*E11	=H30+E11
31	=$E$21*E12	=$F$21*E12	=H31+E12
32	=$E$21*E13	=$F$21*E13	=H32+E13
33	N(P/0)	DN(h)	N(OP)
34	=((B34+F34)/C15)+D15	=MAX(D34,F34)	=B34+H34
35			
36			
37			

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APPENDIX D

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13. ABSTRACT *(Maximum 200 words)*

This paper describes a simple, spreadsheet model for estimating the number of naval units (ships or submarines) needed to meet given requirements for deployments, training and services while also being consistent with maintenance requirements and constraints on personnel operating tempo. A simple cost model is described, and illustrative examples involving the attack submarine force are given.

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